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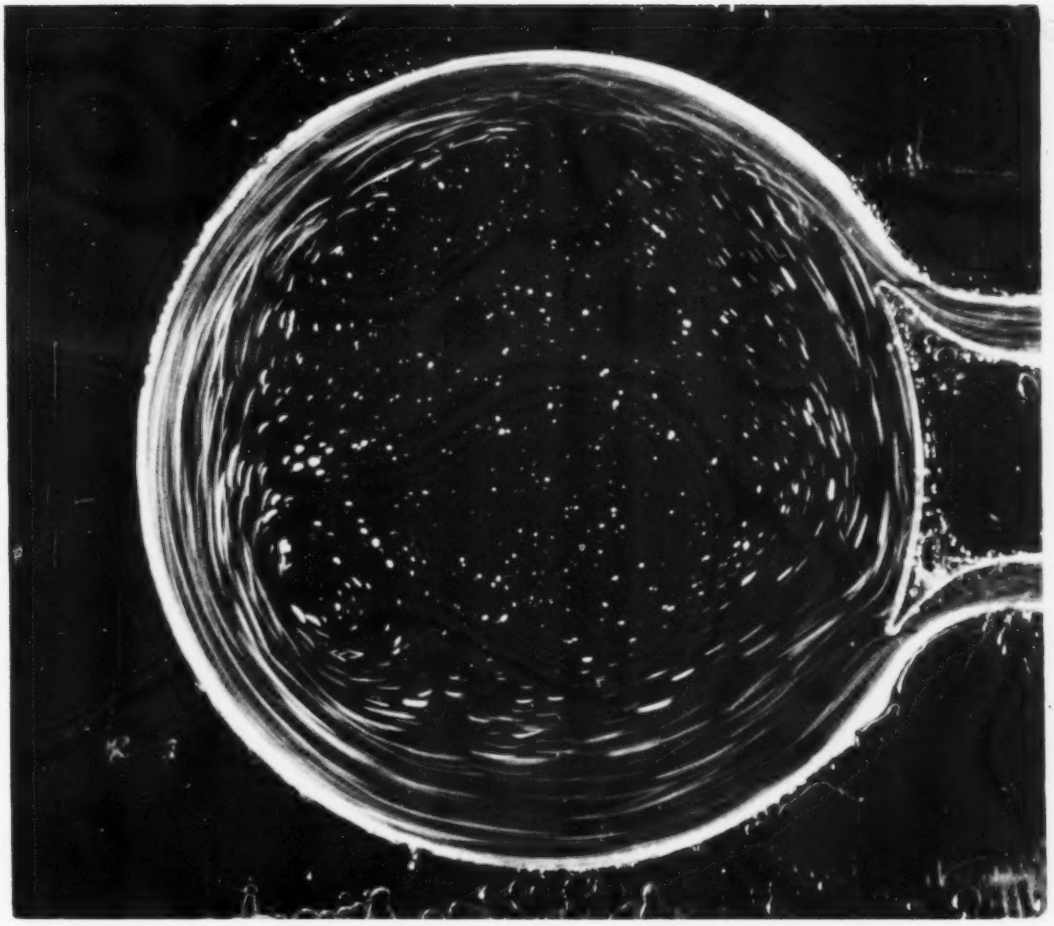

Air Force Systems Command

AIR FORCE research review

NUMBER 1 JANUARY ★ FEBRUARY 1971

ON THE COVER:

"STATIONARY CORE" PHENOMENON in a peripherally driven vortex. For a discussion of this photo, see the section on Taylor's Vortex Experiment in the article, "Rotating Flows."

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ETHEL GAMER, *Editor*

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table of contents

ROTATING FLOWS 1
Siegfried H. Hasinger
Energy Conversion Research Laboratory, ARL

AIRCRAFT WAKES: A NEW LOOK AT A CLASSICAL PROBLEM 4
Colonel W. L. Shields
Development Plans and Analysis Group, Headquarters USAF

A NOVEL ELECTRO-OPTICAL ROTATION SENSOR 8
Dr. R. G. Newburgh, Microwave Physics Laboratory, AFCRL
Dr. T. E. Phipps, Jr., Naval Ordnance Laboratory

HUMAN RESOURCES DATA IN SYSTEM ANALYSIS AND DESIGN 9
Dr. William B. Askren
Advanced Systems Division, Air Force Human Resources Laboratory

MEASUREMENTS OF SURFACE IRREGULARITIES AND SPIN DYNAMICS OF THE PAGEOS BALLOON-SATELLITE BY PHOTOELECTRIC PHOTOMETRY 13
Richard C. Vanderburgh
General Physics Research Laboratory, ARL

TIME SERIES ANALYSIS AND STATISTICAL METEOROLOGY 17
Lt Colonel William R. Trott, AFOSR
Dr. Leon J. Gleser, Johns Hopkins University

READERS INTERCHANGE 22
Speculative Ideas 23
Invention Disclosures 25
Research Needs 27

rotating flows

SIEGFRIED H. HASINGER
Energy Conversion Research Laboratory, ARL

Introduction

Rotating flows occur wherever the fluid state can be identified. They are a subject of widespread interest under investigation in astronomy as well as in sciences concerned with the microstructure of liquids. Oceanography and meteorology, pioneers in the field, have contributed most to the understanding of rotating flows from the viewpoint of common fluid dynamics. Basic aspects and typical behavior of rotating flows will be discussed in this article.

Basic Problem

Of interest are the movements of a fluid in response both to the condition on its boundary and to its internal properties when its principal movement is one of steady rotation around an axis with an essentially fixed direction. The flow movements under such conditions are remarkable because of their unexpected nature. The human mind appears not to be very perceptive to the forces that determine the inertial movement of masses in a rotating system. The behavior of a rotating system, as simple as that of a spinning toy gyroscope, remains strange to our intuition even if we know the laws determining its movement.

By comparison, the conditions are much more involved in the fluid systems contemplated here. A particular feature is that the inertial forces associated with the rotational movement are balanced by fluid pressure forces. In maintaining force equilibrium in the rotating fluid system, the interaction between these forces has the effect of propagating flow disturbances in preferred directions and, in particular, of spreading from boundary to boundary in the direction of the axis of rotation. Viscous effects acting on the boundary, as well as in the interior of the fluid, lead to secondary flow movements which may encompass the entire system. In the analytical treatment of rotating flows, movements on the boundary cannot be separated readily from the main flow, as is done in common boundary layer theory. These complex flow conditions not only prevent a qualitative understanding of rotating flows from intuitive considerations, but also render mathematical descriptions very complex. The quite numerous publications in the field indicate intense activity in the analysis of rotating flows. Although great progress has been made, much work remains to be done.

The decisive tool in early investigations of the dynamics of rotating systems in general was provided by Coriolis in 1853 when he discovered the forces named after him. These forces determine the movement of a body relative to a rotating frame of reference. They explained the behavior of bodies moving on our rotating earth, e.g., Foucoult's pendulum and bodies in ballistic flight. They also brought a basic understanding of global currents in the oceans and in the atmosphere, the principal object of study for rotating flows from the beginning of this century to the present. A prominent example of the continuing effort in this field is the recent discovery of the jet stream explained as resulting from earth's rotation in connection with thermal convection in the atmosphere.

Famous names in oceanography and meteorology, respectively, are V. W. Ekman and C. G. Rossby. (Mr. Rossby is also credited with identifying and explaining the phenomenon of the jet stream.) The important characteristic numbers occurring in the analysis of rotating flows have been named in honor of these investigators. The Ekman-number is a measure of the influence of the viscous forces in relation to the Coriolis forces in a rotating fluid system. The Rossby-number compares the inertial forces exerted relative to the rotating system with the Coriolis forces. In most cases of interest, the Ekman-number is very small, i.e., the Coriolis forces play a dominant role against the viscous forces.

Taylor's Vortex Experiment

In 1923, G. I. Taylor, inspired by theoretical work on rotating flows by J. Proudman, demonstrated a surprising behavior of rotating fluids under laboratory conditions (1, 2). In a closed rectangular container, completely filled with water and rotating at a constant speed, a small disc with a height about equal to its diameter was moved across the bottom of the container by means of a screw shaft driven by a small motor. He observed the following phenomenon: All the fluid above the disc moved as a vertical column, made visible by a dye, with the disc; no fluid surrounding the column penetrated into it. This is the well-known Taylor-Proudman column. It is caused essentially by the action of the Coriolis forces against the liquid pressure forces, and not only exemplifies the surprising behavior of rotating flows, but also demonstrates one of the most basic features of such flows. This feature is the two-dimensional constraint imposed on the movements

of fluids in a rotating system, already referred to in connection with the spreading of disturbances in rotating flows. It tends to make the radial flow fields the same all along the axis of rotation. Only strong viscous or unsteady effects can offset this trend.

Taylor's experiment is also of interest outside the field of common fluid dynamics. The Taylor-Proudman column has been, for instance, considered as the phenomenon responsible for the generation of the great red spot observed floating on the top of the planet Jupiter's opaque atmosphere (3). It is only a part of the unexplained phenomenon that the atmospheres, not only of Jupiter but also of the sun, exhibit remarkable differences in their rate of rotation over their latitudes. This rotational flow problem has occupied astronomers for more than a hundred years.

The trend for two-dimensionality is not always readily apparent in rotating flow systems, as the following example will show. In a stationary vortex chamber, the cross section of which can be seen in the figure 1 photograph, water enters at the periphery through a slot which extends over the entire length of the chamber. After flowing along the periphery of the chamber and transmitting momentum to the water inside the chamber by viscous shear, the water leaves the chamber again on the periphery through a slot which has the same dimensions as the inlet slot. After a sufficiently long operation of the chamber, all the fluid in the chamber would be expected to rotate more or less as a solid body. The observed flow pattern in figure 1 is strikingly different: The fluid in the center portion, extending over more than half the diameter of the chamber, does not rotate at all; the chamber is very short in relation to its diameter. However, much longer chambers, having a length of several chamber diameters, exhibit the same basic feature that the fluid rotation in the center is greatly reduced as compared with the rotation in the outer regions of the chamber in the same way all along the length of the chamber. This basic flow structure is very nearly independent of the through-flow conditions for the chamber. For an explanation of this behavior, the conditions can be related to Taylor's experiment. The flow disturbances are, in the present case, produced by the stationary side walls. Their influence extends, as in the case of the moving disc, over the entire axial extent of the chamber, presenting fluid rotation in the center region.

Figure 1. "Stationary core" phenomenon in a peripherally driven vortex.

Exactly the same flow pattern is obtained in a rotating container filled with water, where the side walls are made non-rotating. However, if, in the case of the jet-driven vortex, the flow through the chamber is shut off, the previously more or less stationary core picks up rotation and the entire chamber content rotates by its own inertia as a solid vortex until it is stopped by wall friction. Under this condition, the Coriolis forces apparently become negligible and viscous forces determine the flow pattern.

The herein described "stationary core" phenomenon is more than a laboratory curiosity. It occurs in any peripherally-driven vortex, as for instance, in the flow behind a step and in the cavity vortex. Theories that neglect the influence of side walls predict a higher rotation in the vortex than experiments show.

The Bath Tub Vortex

Probably the most familiar type of rotating flow is the "bath tub vortex" which invariably forms when liquids are drained from a container. The speed of rotation increases in this vortex toward the center in compliance with the law of conservation of angular momentum. This law implies that the rotation in the vortex comes from rotation already present in the container from which the fluid is being discharged. Even if we bring the fluid to rest, the vortex will form, because the fluid still has the rotation given to it by the earth's rotation. In experiments in which water in a large tank

was allowed sufficient time to come to rest and was then drained, it was found that a consistently counter-clockwise vortex formed in accordance with the earth's rotation and providing that the experiment is located in the northern hemisphere. The earth's rotation is responsible for the formation of large-scale atmospheric vortices like hurricanes, which always turn counter-clockwise, corresponding to their occurrence in the northern hemisphere. A thermal process in the atmosphere maintained by the heat of condensation of water vapor produces an upward flow which acts as a kind of discharge process.

The "bath tub" type vortex is scientifically known as a free or potential vortex. A fluid element in the vortex is free of rotation; i.e., a fluid element deforms in such a way that a diagonal of the element retains its direction in the deformation process. However, an element has rotation if it contains the center of the vortex; i.e., the vortex as a whole has rotation. As we will see later, the above considerations have a very practical aspect if the flow contains particles. For its adjustment to the boundary conditions, the vortex forms a region in its core where the fluid rotates like a solid body. This region also carries an essential part of the through flow.

The free vortex (as we are calling this type of rotating flow) is again subject to the two-dimensional constraint, as explained before, in the sense that the radial flow field is the same along the vortex no matter what shape the axis itself may have (as, for instance, in the well-known ring vortex from smoke rings). This condition determines the familiar shape of atmospheric vortex phenomena, ranging from little twisters to tropical storms. Water spouts are a particularly good example of two-dimensionality. They have been observed to extend from the surface of the sea up to the cloud cover, with a nearly constant diameter of not more than 10 feet for the core, made visible by water droplets carried along in it (4).

The two-dimensional constraint acting on the free vortex also explains the baffling phenomenon of jet engines operating on the runway and ingesting objects like nuts and bolts from the ground. Due to normal wind movements in the surrounding air, sufficient rotation is always present to cause vortex formations in the air rushing toward the jet inlet. Under steady-state conditions as a consequence of the two-dimensional constraint, the twister-like vortex, which forms in this way, must extend from the jet intake to the boundary of the vortex medium, which is in general the ground surface. From previous indications, it is obvious that the disturbance caused by a vortex which would end in mid-air must propagate to the boundary of the vortex medium (this requirement can actually be derived in different ways; it is already an essential ingredient of the famous vortex laws which Helmholtz discovered in 1958, when starting from electrodynamic considerations). The adjustment of the vortex flow to the boundary conditions creates the peculiar situation that practically no inflow occurs along the bulk length of the vortex and the inflow is restricted to the region on the boundary where the vortex touches the ground (5). Thus, the vortex acts like a tube carrying an air current up from the ground, strong enough to lift up bolts and nuts.

The near-zero inflow condition for a free vortex has a peculiar counterpart. As experiments have shown, very small particles like fine dust, which should be centrifuged out of the vortex, actually move toward the vortex center despite the lack of inflow to carry them along. This phenomenon has been observed only recently. An understanding of the process has been obtained from considerations which take into account the above interference of the particle with the no-rotation condition in the free vortex. This interference, in connection with viscous effects, produces fluid pressure forces which can override the centrifugal forces and drive the particles toward the center.

Although rotating flows have been studied quite intensively over the last hundred years, many important fluid flow phenomena involving rotating flows are still in need of explanation. A prominent phenomenon is ordinary flow turbulence which, in its elemental structure, is composed of rotating flow elements. A complete understanding of the origin and basic mechanism of turbulence is still lacking. It is interesting to note that rotating flows have a tendency to suppress turbulence. For instance, in a cyclone separator in which a highly turbulent flow feeds a free vortex, the degree of turbulence becomes greatly reduced inside the vortex. One might, therefore, speculate that the rotating flow elements which make up a turbulent flow, as mentioned above, are free of turbulent subelements; i.e., they have a laminar character.

Other Rotating Flow Phenomena

The list of remarkable phenomena in rotating flows can be extended further: The vortex cooling effect discovered by G. Ranque in 1933 is one of the most publicized. Another interesting phenomenon is that of sound waves being scattered by a vortex—an effect of importance in low-temperature physics for the diagnosis of vortex elements. A related effect is the generation of sound by vortices, an effect of concern in the field of noise abatement for jet engines. The remarkable feature is that these various flow phenomena all have a common basis. They represent a part of the mechanism which provides equilibrium between the Coriolis forces and the fluid pressure forces in a rotating fluid system.

Colloid Core Nuclear Reactor

The Energy Conversion Research Laboratory is quite concerned with many of these vortex flow phenomena in its work on "colloid," or more generally speaking "dispersed," nuclear core reactors intended for use as rocket propulsion devices or other high-temperature nuclear heat sources. Rotating flows are used in such reactors to contain fissionable material in finely dispersed form in a cavity in a

sufficient amount to establish criticality. The flow medium is a low-molecular-weight gas like hydrogen which passes through the cloud of nuclear fuel particles to take up the heat produced by the nuclear reactions in the cloud. This type of reactor is able to produce higher gas temperature than is possible with the solid core reactors already in operation, with the consequence that the specific impulse of nuclear rockets can be raised to 1000 seconds and possibly higher.

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Mr. Siegfried H. Hasinger has been a research scientist in the Energetics Research Laboratory, ARL, since 1952. He graduated in 1937 as a Dipl. Ing. from the Technical University in Munich, Germany, majoring in Technical Physics. Subsequently, he joined the Deutche Versuchanstalt für Luftfahrt (German Research Establishment for Aeronautics) in Berlin-Adlershof, Germany, where he remained until 1945 engaging in theoretical and experimental research in the fields of jet propulsion, general fluid dynamics, and thermodynamics.

In 1947, under the "Paper-clip" organization, he joined the Air Material Command (now AFLC) Intelligence Division at Wright-Patterson AFB for one year and subsequently transferred to the then existing "Equipment Laboratory" at that base. His research activity during this time extended to problems in thermodynamics and fluid dynamics of jet propulsion, heat transfer, infrared radiation, and condensation. He later joined the Aeronautical Research Laboratory, predecessor of ARL, where he engaged in research on vortex devices and peripheral pumps, monitoring also a series of research contracts on turbo-machines and pump cavitation.

More recently, Mr. Hasinger has been active in theoretical and experimental research in the fields of electrofluid dynamic energy conversion, momentum transfer by shear forces, condensation phenomena, vortex flow, and thrust augmentation.

Mr. Hasinger has published a number of organizational reports as well as scientific journal articles about his various research activities.

Aircraft Wakes:
A New Look At A Classical Problem

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Introduction

That aeronautical research has endured some hard times during the first decade of the space age seems to be widely recognized, as evidenced in many ways: policy statements by major technical societies; remarks by spokesmen from industry and Government; and to some extent, redirection of program efforts and manpower resources, shifting emphasis from space research to aeronautical research. No manpower allocation could illustrate this point better than the reassignment of Mr. Neil Armstrong to the post of Deputy Associate Administrator of NASA for Aeronautical Research less than one year from the time he took that "one small step for a man."

In a very direct sense, research and interest on aircraft wake turbulence also symbolize this new emphasis. The hiatus in aeronautical research has indeed caused a lapse in our national research programs – a lapse not easy to overcome. During the recent lean years of aeronautical research, many scientists and engineers have turned to new disciplines. It will not be easy for them to turn again to aeronautical research, nor for us to educate a new generation of aeronautical scientists.

Some examples will illustrate the need for new aeronautical research. In 1951, the standard references for both theoretical and experimental (including operational) calculations of the effects of aircraft-induced vortices were the papers by Spreiter and Sacks (1) and by Bleviss (2). In 1951, the B-47, a 200,000-pound airplane with a speed of about 500 knots, represented the state of the art in aircraft design. Twenty years later, the Concorde, 385,000 pounds and Mach 2.2; the C5A, 728,000 pounds and 500 knots; and the B2707-300, 635,000 pounds and Mach 2.7, are the representatives. Although excellent work has been done since 1951 on a few topics in wake vortex research, the same two papers still fairly well represent the extent of our fundamental knowledge.

Questions not related to aircraft design demand a new look at the aircraft wake problem. The Air Force is faced with a whole new set of problems, such as high-density mixed traffic operations, aerial refueling, and air drops from high performance aircraft.

**In 1969, Colonel Shields, as project scientist in the Mechanics Division, directed the AFOSR program of research in wake turbulence.*

The Federal Aviation Administration must deal with corresponding operational problems in civil air operations. The greater size and higher performance of civil transports, together with the increase in traffic density of both the transport and general aviation fleets, have greatly increased the attention given to potential wake hazards (3, 4).

Other groups are concerned with the interaction of aerodynamic vortices with the environment. For example, the effects of local meteorological conditions will undoubtedly have major significance in predicting the motion of aerodynamic vortices. Local weather modification by means of aerodynamic forces is already a reality in some limited applications (5). Pollution problems too are now gaining increased attention. Aircraft engine smoke is perhaps the major current consideration, but inevitably someone will characterize the aircraft wake as a problem of vorticose pollution.

These considerations, some scientific, some operational, provided the incentive about two years ago for the Air Force Office of Scientific Research to initiate a program of research in aircraft wakes. This paper is intended to suggest a frame of reference, first by elucidating some historical aspects of the aircraft wake problem, then by recounting the genesis of the AFOSR wake turbulence research program, and finally by commenting briefly on some of the challenging research opportunities contained within the wake problem. Photographs appearing in this article were obtained from the Federal Aviation Administration; they illustrate some of the problems to be considered.

Reflections on Some Seemingly Simple Problems in Fluid Mechanics

The early visualization of a two-dimensional rollup of a vortex sheet has given way to a complex three-dimensional picture. The Karman vortex street is a good example of complexity in a seemingly simple problem. Vortex shedding in the wakes of cylinders was observed long ago, and Karman himself tells of an old Italian painting that shows the phenomenon (6). Karman's theory (7) for a stable row of vortices provided a relatively simple explanation of observations; however, continuing analysis has greatly refined the theory (8) and experiments have shown the structure of the vortex street to be more complicated than the simple flow visualizations suggested (9, 10). Each new research effort seems to reveal new degrees of complexity.

Another example of a seemingly simple problem in classical fluid mechanics is the edgetone, the fluid dynamic sound phenomenon that occurs when a thin two-dimensional jet impinges upon a sharp edge. It was

Figure 1. Entrained jet exhaust marking wake of a departing aircraft.

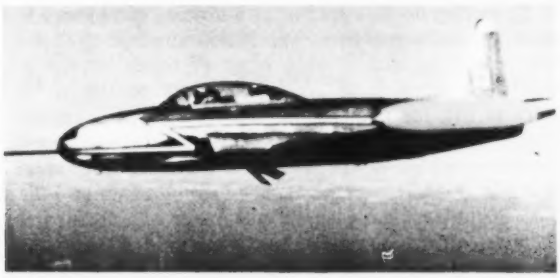

Figure 3. Canadian T-33 measurement aircraft used during FAA testing (note nose-mounted probe).

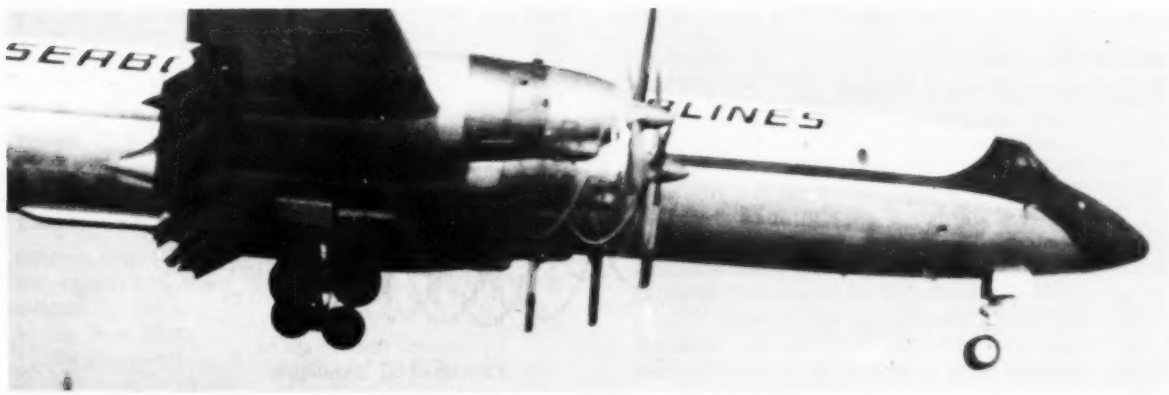

Figure 2. Prop tip vortices made visible by condensation.

discovered by Sondhaus (11) in 1854; many explanations of the phenomenon have since been offered. Each study of the problem has revealed further complexities. It was pointed out by Shields and Karamcheti (12) that almost every edgetone study since 1854 has stated the need for additional study of new aspects of the problem. No satisfactory theory of the apparently simple edgetone has yet been developed.

The aerodynamic vortex fits this pattern of unfolding complexity. Lanchester (13) was apparently the first to explicate the role of vortex formation in the generation of lift by an airfoil. His drawings and accompanying physical explanation seem simple and straightforward. The first analytical treatment by Prandtl (14) was correspondingly simple. Each subsequent experimental and theoretical study has revealed added complexities, providing an apparently endless list of problems for further research. The two-dimensional problem, addressed initially by Lanchester and Prandtl, has evolved into a complex three-dimensional problem. The inflight measurements of McCormick et. al. (15) have shown the actual aircraft vortex to have a complex structure with several major regions of distinct behavior. Batchelor's (16) analysis demonstrates the fundamental importance of three-dimensional considerations. Work by Donaldson and Snedeker (17) has shown how aerodynamic vortices may have a multi-cellular structure, thus introducing a higher order of complexity. Vortex stability, discussed recently by Crow (18), has also emerged as a major consideration.

Reflecting on this pattern of unfolding complexity in seemingly simple problems, one is not surprised to find a need to address such a wide range of topics related to aerodynamic vortices. A problem, initially limited to the theory of lift, has expanded to encompass hydrodynamic stability, geophysical flows, unsteady aerodynamics, and aircraft operations. Indeed, synergism among research areas in mechanics has become a familiar pattern. Consider the fusion of the apparently unrelated subjects of air loads and structures into the science of aeroelasticity, and the merging of chemistry, electromagnetism, and aerodynamics into magnetogasdynamics. It seems likely that vortex research and aerodynamics will follow the pattern and combine to provide new techniques of vortex control.

Genesis of the AFOSR Wake Turbulence Research Program

Aerodynamic vortices associated with generation of lift by airfoils began early in the history of heavier-than-air flight. Summaries of theoretical and experimental research and practical applications may be found in a number of papers. These efforts, by and large, kept pace with other developments in the science of aeronautics. However, in this historical context, aerodynamic vortex research during the past decade was somewhat of an anomaly. Although numerous questions arose because of the increased size and speed of modern aircraft, only a limited amount of research was carried out. Reflecting upon this situation several years ago, scientists at AFOSR singled out aircraft wake turbulence as a promising area of concentration in rejuvenating their aerodynamics program.

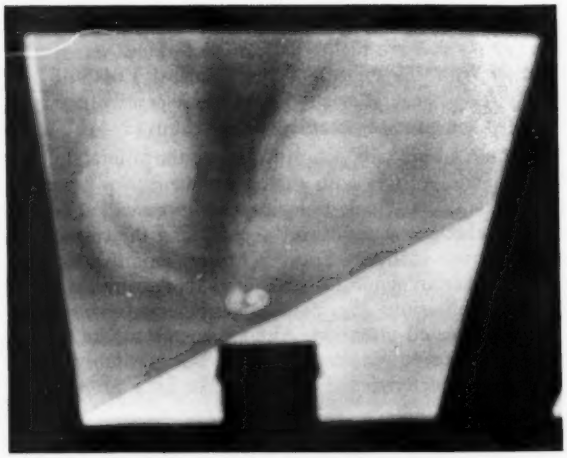

Figure 4. Contrail-outlined wake of a C-135 viewed from following aircraft.

Figure 5. Contrail-outlined wake of a C-141 viewed from a following C-141.

Promising Wake Turbulence Research Topics

At the outset, AFOSR scientists found that research problems associated with aircraft wake turbulence seemed to fall naturally into several major categories:

1. Formation of trailing vortices
2. Decay and breakup of vortices
3. Interaction with the environment
4. Operational considerations
5. Experimental techniques

Each of these categories encompasses theoretical, experimental, and practical problems that are very nicely integrated.

Formation of trailing vortices seems to be a promising research area because it contains so many unanswered questions, such as the role of the boundary layers and boundary layer disturbances in vortex rollup; the effect of wing sweep and taper and wing loading on vortex development (with implications for vortex control); and scaling of vortex parameters as functions of time, space, and wing geometry. Determination of the appropriate viscosity for turbulent vortices is another important problem. More attention might be given to the birth process of a vortex, with a view toward cancellation of the vortex rollup before or as it occurs. Control of vortices depends upon understanding the basic fluid motions involved in vortex formation and upon developing equipment and techniques to modify those motions. Finally, vortex control of aircraft will demand a better knowledge of both vortex motions and the interaction of vortices with lifting surfaces. It is not beyond the realm of speculation that vortex considerations might one day be as much a part of aircraft design philosophy as L/D.

A logical area of research, because it has both scientific and operational implications, is the decay and breakup of vortices. The scientific problems include the nature and origin of instabilities, the significance of external perturbations, and the interaction of paired vortices. The operational implications also seem clear: knowledge of the mechanism of breakup could lead to control of breakup, and reliable avoidance of wake encounters can only be accomplished after more is known about the theory of vortex motion and decay and after means are developed to detect and track a vortex. Study of the decay process should be extended to include the final state of a vortex. Furthermore, we may not always be interested in the decay and cancellation of vortices; in geophysical applications, for example, the goal might be a more intense and persistent aerodynamic vortex.

Interaction with the environment in many ways seems to offer the widest range of challenging problems. These include atmospheric effects on vortex decay and breakup, wake energy coupling into natural atmospheric processes, a possible artificial source of clear air turbulence, and even the possibility of weather modification.

Operational considerations appear in each category of wake turbulence research. Assuming that operational needs will include prediction, detection, avoidance, control, and induced dissipation of vortices, then these needs will be satisfied only on the basis of improved understanding of the birth, life, and death of vortices.

Finally, experimental techniques in wake turbulence research must be improved. One research goal is to increase the validity of flight and wind tunnel measurements, establishing the relationship between them in the form of scaling laws. There are substantial difficulties at present in scaling, even between aircraft of similar weight and size. Scaling of vortex parameters from models to aircraft and from small aircraft to large aircraft presents some difficult problems. Another research goal is the improvement of the experimental technique of flow visualization to increase our understanding of aerodynamic vortices.

This initial categorization of topics in wake turbulence research served fairly well to structure the AFOSR research program. Although it is now several years old, it is still proving useful.

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A Novel Electro-Optical Rotation Sensor

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The navigational needs of modern aircraft, missiles, and satellites have made rotation sensors a necessity in today's technology. Although most of these needs are filled by the modern developments of the gyroscope, recent work has been done with the ring laser. The gyroscope is an essentially mechanical device whereas the ring laser is electro-optical in nature. Recent work in the Microwave Laboratory of AFCRL and the Naval Ordnance Laboratory has suggested a novel electro-optical approach to the problem of rotation sensing, quite different from that of the ring laser.

The starting point of the new method is the reflection of polarized light from a dielectric. If light, linearly polarized in its plane of incidence, is incident on a refractive medium at an angle whose tangent equals the relative index of refraction, there is no reflected ray and the refracted ray direction is perpendicular to the would-be reflected ray. This particular angle of incidence is called the Brewster angle. The phenomenon is well known in classical optics.

If the Brewster condition is satisfied for a system in which the source, refractive medium, and observer are all at rest, the sum of the angle of incidence and the angle of refraction is 90 degrees. It is true that the absence of the reflected beam is independent of the state of motion of the observer with respect to the medium. No observer, regardless of his state of motion, will see a reflected beam. However, an observer moving uniformly with respect to the medium will not measure the sum of the two angles of incidence and refraction as being 90 degrees.

This phenomenon, called aberration, has been curiously neglected in terrestrial applications. In astronomy, its importance has been recognized since the early eighteenth century. It played a most important role in the astronomical experiments that led to the Michelson-Morley experiment which demonstrated conclusively the nonexistence of the luminiferous ether. But little or no effort has been made to utilize aberration as a laboratory tool.

If we designate the angle of incidence as θ_1, and the angle of refraction in the frame K_1 as ϕ_1, the Brewster condition may be expressed as $\tan\theta_1 \tan\theta_1 = 1$. As we have said, the absence of a reflected beam does not depend on the state of the motion of the observer. Owing to aberration, an observer with respect to whom the system moves will measure new angles of incidence and refraction, the product of whose tangents will not equal unity. To determine those angles requires Lorentz transformation of the wave-number 4-vector. This transformation is carried out in detail in a paper by Newburgh and Phipps (1). Designating the angles, as measured by the observer who moves with respect to the system, as θ_2, and ϕ_2, we find that

$$\tan\theta_2 \tan\phi_2 = \frac{1}{\left(1 - \frac{v^2}{c^2}\right)} [1 + v/(c \sin\theta_1)]^2$$

where v is the velocity of the medium and c is the velocity of light. For $v \ll c$, we may write the relation as

$$\tan\theta_2 \tan\phi_2 \approx 1 + 2v/(c \sin\theta_1) + \cdots$$

Since $\sin\theta_1$ is always less than or equal to unity, its presence in the denominator insures that $2v/c$ is the minimum value of the deviation of the product from unity.

This result, which is of theoretical importance in shedding light on the meaning of the Einstein velocity addition law, is discussed at length in the paper by Newburgh and Phipps. The possible experimental verification of the effect is of interest in the field of rotation sensing and may lead to increased sensitivity. Of especial interest is the absence of the reflected ray when the Brewster condition is satisfied. If an experiment can be designed such that the Brewster condition is first satisfied and then violated, the would-be reflected ray would then appear and be detectable.

As such an experiment, consider the following arrangement. Let a ray of linearly polarized light fall upon the edge of a disk of dielectric such as quartz, so that the Brewster condition is satisfied while the disk is at rest. A detector

looking in the direction of the would-be reflected ray would observe nothing. Then set the disk rotating about its center. If the dispersion curve of the medium is flat in the wavelength region of the incident light, the index of refraction of the medium does not change. Hence, the Doppler shift of the frequency in the moving medium would not affect the direction of the refracted beam. However, there would be an effect on the direction owing to the disk motion, as shown by our analysis. Hence, the Brewster condition would no longer be satisfied and a reflected beam would appear. Its direction would be a function of the disk velocity, and therefore of the rotational angular velocity. By changing the angle of incidence by an amount proportional to v/c, we could again satisfy the Brewster condition and eliminate the reflected ray, thereby performing a null experiment.

Although this experiment is possible in principle, among several practical problems to be considered are the surface imperfections which will permit some small amount of reflection, even at the Brewster angle. The rotation of the disk itself can affect the index of the material, owing to stresses set up by rotation. In addition, the rotation, because of the induced vibration, may affect the measurements of angles.

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Dr. Ronald G. Newburgh is chief of the Electromagnetic Sensors Branch of AFCRL's Microwave Physics Laboratory. He joined AFCRL in 1961 and spent one year (1964–1965) at the Service D'Aéronomie, Verrières-Le-Buisson, France, where he worked on the theory of radiation. He is currently working on rotation-sensing experiments based on electromagnetic theory and on problems of the physics of rotating systems.

He was graduated in 1945 from Harvard College where he majored in Chemistry. Subsequently, he studied at the Physikalisch-Chemisches Institut, University of Zuerich, and in 1959 received his Ph.D. in Physics from the Massachusetts Institute of Technology. Dr. Newburgh was associated with private industry and with the Naval Research Laboratory.

He is a member of the American Physical Society, the Optical Society of America, and Sigma Xi, and the author and coauthor of many publications.

Human Resources Data In System Analysis And Design

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Formerly, skilled manpower for military systems was provided only after the hardware was delivered to the military unit. Personnel selection and training were accomplished as a form of *reaction* to the demands of the equipment. Today, because of system complexity and the faster pace of events, human resources planning is characterized by analyses which *predict* manpower needs early in system development life. This procedure allows personnel selection and training to begin before the hardware is delivered to the field (1).

But what will be the nature of human resources planning for military systems in the 70s? Very likely, it will be a design-parameter approach in which data on personnel and training resources will be used to influence the configuration characteristics of new systems. This new approach is evolving because of the growing recognition that human resources have a substantial impact on dollar costs and operational capabilities of systems. For example, personnel costs account for 47% of the 10-year direct support costs for one B-52G wing, and the "on-alert" costs of an Air Force Minuteman missile squadron are divided equally between manpower

and hardware (2, 3). In addition, a zero draft law could alter greatly the quantity and quality of manpower volunteering for the Air Force, thus requiring systems that are designed to be operated and maintained by a "new generation" personnel force.

Consequently, the Air Force Human Resources Laboratory has been performing research in this problem area. The research has as its goal the development of a technology which will allow the integrating of data on the actual and potential human resources of the Air Force with data on engineering, logistical, and operational requirements in system analytical studies and design activities.

Research to date has . . . identified the kinds of human resources data which are useful in the system development process . . . determined that it is feasible to impose human resources data as constraints on the design engineer . . . determined what effect these constraints have on system characteristics . . . and determined the elements of a procedure for integrating human resources data in the system development process.

Kinds of Human Resources Data

The human resources information and data which have been found useful for system development activities describe: personnel skill types (occupational groups such as avionics maintenance and computer programing) available in the Air Force, proficiency levels (e.g., apprentice, technician, and senior technician) of the skill types, task duties of the skill types and skill levels, and performance capabilities (such as time and errors) of the task duties. Human resources data also describe: the quantity of personnel of the various skill types and proficiency levels available in the Air Force, productive labor hours available from the skill types and skill levels, training time and costs to develop specified skill proficiency levels for the various skill types, and total dollar costs of providing personnel for each skill level throughout the life cycle of systems.

Human Resources Data as Design Parameters

It has been well established that human resources data, when included as constraints in the statement-of-work, significantly affect the engineer's design outputs. In one study involving the simulated design of the propellant transfer and pressurization subsystem of a ballistic missile, two teams of engineers were given different human resources constraints in the statement-of-work (4). One team received, in addition to the normal engineering requirements, the goal of designing the subsystem to require a small crew with high skill. The other team received, in addition to the normal engineering requirements, the design goal of a large crew with low skill.

When the design outputs of the two teams were evaluated, it was found that the team with the small-crew/high-skill requirement had produced designs that included fewer human functions, fewer pieces of manually operated equipment, and interestingly enough, more control-display hardware items (table 1). The control-display hardware indicated a use of the decision-making ability inherent in high-skill personnel.

Other analyses of the designs indicated that the large-crew/low-skill team produced designs that had higher predicted equipment reliability and human reliability for operation of the subsystem. This fact is explained by the use of simpler equipments and simpler human operations by the designers in an attempt to compensate for the low skill of the personnel who would operate the subsystem.

Another study, this time the simulated design of the maintenance equipment of an (aircraft-launched) air-to-ground missile, confirmed that human resources constraints affect design outputs of engineers (5). Three teams of designers were set up: Team 1 received a typical engineering statement-of-work containing minimal reference to human requirements, Team 2 received the basic statement-of-work plus a constraint on the maximum number of personnel, and Team 3 received the statement-of-work plus a maximum skill level constraint.

An analysis of the design products of the three groups indicated that different system characteristics resulted from the different constraints added to the statements-of-work (table 2).

Team 2, with the manpower constraint, when compared with the base-

Table 1

Impact of Manpower and Personnel Skill Constraints on the Design Characteristics of a Ballistic Missile Subsystem

Manpower and Personnel Skill Constraint (3 Designs Each)	Average Design Characteristics Values: Top-Level Schematic Human Functions	Personnel Operated Equipment Items	Control-Display Hardware Items
Small-Crew/High-Skill	4.7	58.7	161.7
Large-Crew/Low-Skill	7.0	68.0	103.3

Table 2

Impact of Manpower and Skill Constraints on the Design Characteristics of Maintenance Equipment

Human Resources Constraint	Level of Automation	Equipment Characteristics: Average Number of Test Sets	Equipment Characteristics: Average Number of Manual Operations
Team 1			
Baseline– No Human Resources Data (4 designs)	3 Semiautomatic 1 Automatic	5.9	17.5
Team 2			
Maximum Manpower (2 designs)	2 Automatic	3.5	50.0
Team 3			
Maximum Skill Level (2 designs)	1 Semiautomatic 1 Automatic	7.5	50.5

line group (Team 1), produced designs with higher levels of automation, required fewer test sets, and included more manual features. The results, except for more manual operations, are consistent with the quantity constraint. The "more manual operations" result cannot be fully explained, but is interpreted partly as the reaction of the designers to the detailed human resources data put in the statement-of-work. It is reasoned that they were more sensitive to the human element of the subsystem, and were more disposed to create work for man in the system.

Team 3, with the skill level constraint, when compared with the baseline group (Team 1), produced designs with about the same degree of automation, but required more test sets, and included more manual operations. These differences indicate that Team 3 was putting emphasis on providing more specialized test equipment and more manual tasks to utilize the large supply of low-skilled personnel.

The results of another study provide additional understanding of the effect that human resources constraints can have on design (6). In this research, the emphasis was on the specific ways in which the engineer translates skill constraints into system characteristics. It was found that engineers do translate personnel skill constraints into particular design characteristics. For example, the designer translates a low-skill constraint into subsystem characteristics such as built-in test equipment, similar components in one module, go/no-go displays, and short checkout procedures (table 3). On the other hand, the engineer translates a freedom from low-skill constraint, or more precisely, an indication that high-skilled personnel will be available, into characteristics such as quantitative displays, portable test equipment, much information feedback, and special purpose test equipment (table 4).

Another example, taken from the same study, involves the translation of the amount of training to be given to system personnel into relevant design characteristics. It was found that when the engineer is given the information that only a small amount of new training will be provided to system personnel, he incorporates in his design such features as go/no-go information sources, special purpose test equipment, self-check capability, and

Table 3

Equipment Characteristics Related to Unskilled Personnel

- Built-in Test Equipment
- All Similar Components in One Module
- Go/No-Go Displays
- Relatively Short Checkout Procedures
- Internal Components Arranged by Signal Flow
- Step-by-Step Procedure
- Fixed Maintenance Equipment
- Throw Away Maintenance Concept
- Subsystem Checks Which Indicate That the Subsystem Is Either Go/No-Go

Table 4

Equipment Characteristics Related to Skilled Personnel

- Quantitative Displays
- Portable Test Equipment
- Maximum Display of Feedback Information
- Special Purpose Test Equipment
- Maximum Number of Test Points
- Scope Pattern Interpretation Required
- Troubleshooting Down to the Circuit Level
- Component Repair Required
- Onsite Maintenance
- Visual Inspection of Components Required
- Limited Number of Maintenance Personnel
- Calibration Required

modularized equipment. However, if he is told that much training will be provided to system personnel, he incorporates features such as circuit level trouble-shooting, multipurpose equipment, scale-type displays, and individual packaging of components in his design.

In summary, the main finding of this series of studies is that human resources data, when given to the design engineer as constraints in the statement-of-work, have an impact on the characteristics of the system he designs. In addition, it was learned that designing a military weapon subsystem is in many respects a creative and artistic process. In these studies, the engineer conceptualized his design approach very quickly after receipt of the statement-of-work, and he used the balance of the design time to detail his concept. And, like the artist, he resisted making changes, suggested by the researchers, to his original design.

Procedure for Integrating Human Resources Data in the System Development Process

During this research, the elements have begun to emerge of a procedure for incorporating human resources data in system development programs. The process includes these phases:

(1) Determine very early in the conceptual phase of a system the "likely" manpower force to be available during the time period when the system would become operational. This "likely" force would be derived from sources such as systems being phased out, career personnel, new enlistees, and graduates of established training courses.

(2) Later, during the conceptual phase, perform analyses and tradeoff studies which compare the "likely" force with alternate personnel forces of varying quantities and skill types, and determine their impact on the cost, capability, reliability, availablity, etc., of the proposed system. Ultimately, a "desired" manpower structure would be proposed for the system.

(3) Incorporate this "desired" personnel force as human resources constraints in the statement-of-work sent to contractors who are bidding on the system.

The remaining phases of the process include:

(4) Requiring contractors who propose to develop the system to determine the effect of the human resources requirement on their configuration, with contractor selection based partially on their ability to design in accordance with the human resources constraints, or with an acceptable alternative.

(5) Periodic testing for compliance with the human resources requirements as the design and development activities progress.

(6) An operational site test to demonstrate that the "desired" personnel force can operate and maintain the system to the required level of proficiency.

Conclusions

Man is an important parameter in military systems. Although he accounts for approximately 50% of system performance and cost, the definition of his role in systems receives little of the creative engineering effort expended during the development process. It was shown in this paper that data on the human resources of the Air Force can be incorporated in the design process and can have an effect on the configuration of the system. It is concluded that a more extensive use of such data in the analysis and design efforts for new systems would result in systems which are more cost-effective, and which promote a higher morale in the operational forces as a result of fuller use of individual job skills.

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Dr. William B. Askren is employed as a research psychologist in the Advanced Systems Division of the Air Force Human Resources Laboratory, Wright-Patterson AFB, Ohio. He is currently engaged in research on quantifying and measuring human performance, and utilizing human resources data as decision parameters in system analysis and design. Dr. Askren has an A.B. in Mathematics from Wittenberg University and a Ph.D. in Industrial Psychology from Purdue University.

His previous experience includes five years as an engineering psychologist with the Systems Engineering Group, Wright-Patterson AFB, four years on the faculty at North Carolina State University and Wright State University, Dayton, Ohio, and five years as an industrial psychologist with the A. O. Smith Corporation, Milwaukee, Wisconsin.

Dr. Askren is a Fellow of the American Psychological Association, and a member of the Human Factors Society and the Institute of Electrical and Electronics Engineers. He has been certified as a Diplomate in Industrial Psychology by the American Board of Professional Psychology. Dr. Askren has authored more than 30 technical publications.

Measurements of Surface Irregularities and Spin Dynamics of the Pageos Balloon-Satellite by Photoelectric Photometry

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A *PA*ssive *GEO*detic *S*atellite (PAGEOS) was launched during the summer of 1966 as a triangulation target sufficiently high and sufficiently bright to be photographed simultaneously with modest observing equipment at widely separated geographical positions, i.e., intercontinental or transcontinental distances. PAGEOS is a copy of the famous (but no longer orbiting) ECHO I satellite; it is formed as a 30-meter diameter aluminized mylar shell. Since the surface is specular (mirror-like) (1), sunlight is scattered by the balloon in all directions, but essentially all of the light received by a single observer originates from a small (3-inch) virtual image of the sun on the vehicle surface, as shown pictorially in figure 1. (The diffuse scattering by surface imperfections, as implied by the sketch, amounts to less than 5 percent, and can be accounted for accordingly.) Since the observed flux comes from such a small area, the reflecting "hot spot" can be used as a surface-mapping element, providing the time of observation can be related to the position of the reflecting spot on the surface of the spacecraft. The PAGEOS spacecraft rotates on an axis every 3 to 4 minutes. During the 30 to 40 minutes that this rather high satellite can be observed as it orbits each time around the earth, the hot spot traces out 7 to 10 paths about the satellite. During its first 15 months in orbit, we made intensive study of this vehicle at our OPOS (Optical Properties of Orbiting Satellites) Observatory facility at Sulphur Grove, Ohio, to determine its size, reflectivity, shape, and rotation characteristics (OAR Research Review, Vol. VII, No. 10, October 1968, pp. 1-4).

Gradual improvements in our calibration techniques, and recent speculations (2, 3) about an unexpected perturbing force causing the PAGEOS and other balloon-type satellites to move hundreds of miles from their predicted paths, have caused us to look again at the spacecraft to measure (1) its shape with more precision and (2) not only its rate of rotation, but also the orientation of the axis of rotation and the movement of the axis of rotation resulting from perturbing forces. Detailed knowledge of these parameters would be essential to geodesists who wish to correct their data for the parallax effect of the hot spot relative to the balloon center, and to

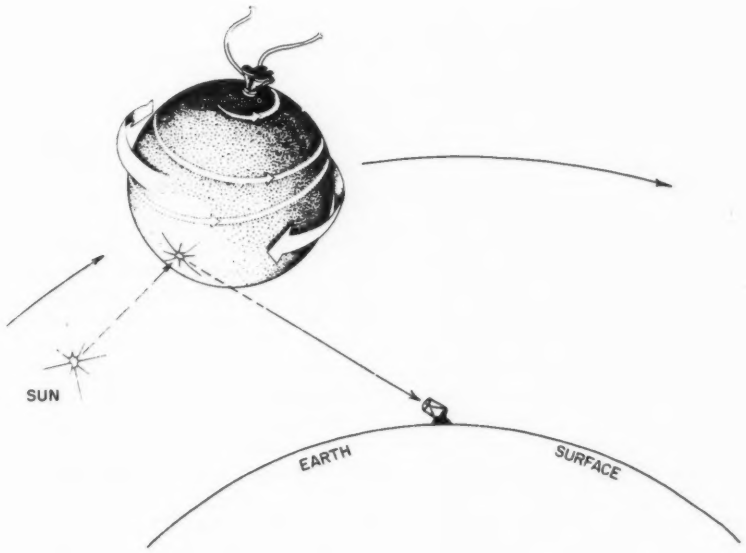

Figure 1. Artist's concept of a sun-illuminated, spinning, specular balloon-satellite observed from a fixed ground site.

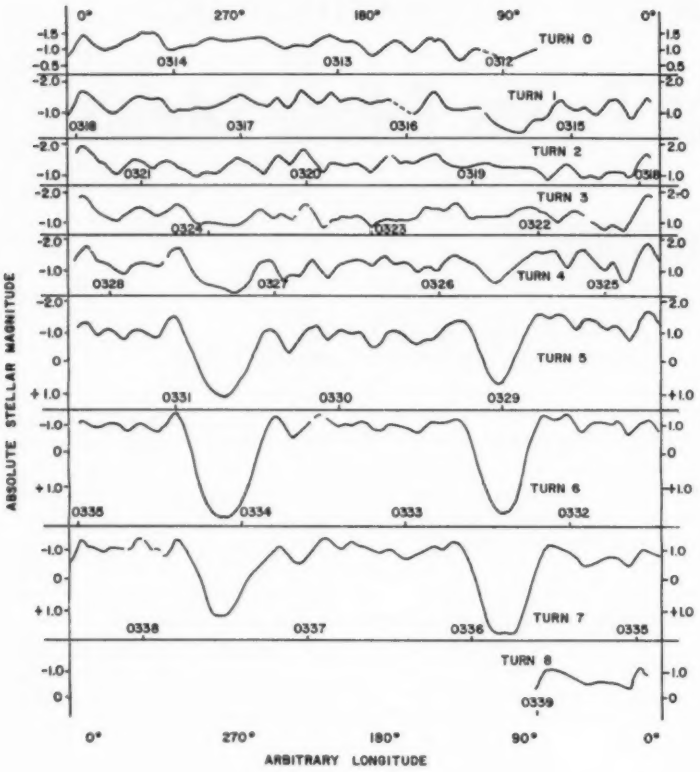

Figure 2. 27 August 1969, reduced light curve (atmospheric extinction removed, normalized to 1000 km slant range).

the orbit analysts who wish to describe the perturbing forces.

This work was in fact undertaken at the request of orbit analysts at the NASA Goddard Space Flight Center. We had begun collecting photoelectric data on PAGEOS as soon as it was launched. The smoothness and constancy of the first few light curves confirmed that a sphere of the design size had been successfully deployed. But within a few weeks, coincident with the transition from continuous solar illumination (and heating) to periodic passage of the vehicle through the earth's shadow, the light curves began to show irregular brightness fluctuations. After a few months, a periodicity in the brightness fluctuations became apparent, suggesting balloon rotation. At 14 months, light curves began to exhibit an evenly-spaced brightness decrease, twice per rotation cycle, to a level as low as 1/16 of the average brightness. This behavior suggested two antipodal regions whose radii of curvature had shrunk from the nominal 15 meters to about 4 meters, implying a football-like shape. While the observed brightness patterns could have been caused by local variations in reflectivity, the required extremes of albedos and their opposed locations on the surface make this conclusion highly improbable. Because the model of an increasingly prolate spheriod rotating about a minor axis is the simplest one that accounts for both the observed effects and their gradual onset, we have adopted it in the following analysis.

Since surface mapping required knowledge of the spin-axis orientation, use was made of the different illumination geometries during successive satellite transits to map "equatorial" bands. During an intensive observation effort from August to December 1969, sufficient data were collected to provide both surface maps and an ephemeris of the spin axis.

Figure 2 shows a typical light curve after reduction of the data to correct for the effects of atmospheric absorption and the varying distance to the spacecraft. Eight successive rotations of the vehicle are seen. With knowledge of the spin axis derived from additional observations three hours later, these brightness data allow the construction of an isophote map on the surface of the spacecraft. Figure 3 shows such a map of lines of constant brightness on the spacecraft. Further interpretation of the isophotes into the local radii of curvature of the mirror-like surface allows inference of a cross section of the distorted balloon. An approximate geometrical reduction yields the equatorial cross section shown in figure 4, which does indeed resemble that of a football and which seems to be reasonably proportionate in size to the nominal cross section of a 100-ft sphere. A more rigorous analytic procedure for constructing a three-dimensional figure from the isophote map is currently in progress.

The important result of this study, however, is the discovery of a regular motion of the axis of rotation about a line joining the satellite to the sun, as had been hypothesized by the orbit analysts in order to explain their mysterious perturbation by radiation pressure. A plot of the spin-axis location during the few months of observation does indeed reveal a coning motion about the sun vector, as shown in figure 5. The effect is to cause the maximum solar radiation pressure to be applied at a "latitude" of -30° on the spinning balloon, and hence a continuous shadowing of the polar region "north" of +60°. Data collected to date indicate a direct coupling between rotation period and spin-axis precession rate, both of which appear to cycle in a manner linked to successive intervals of partial eclipse of the

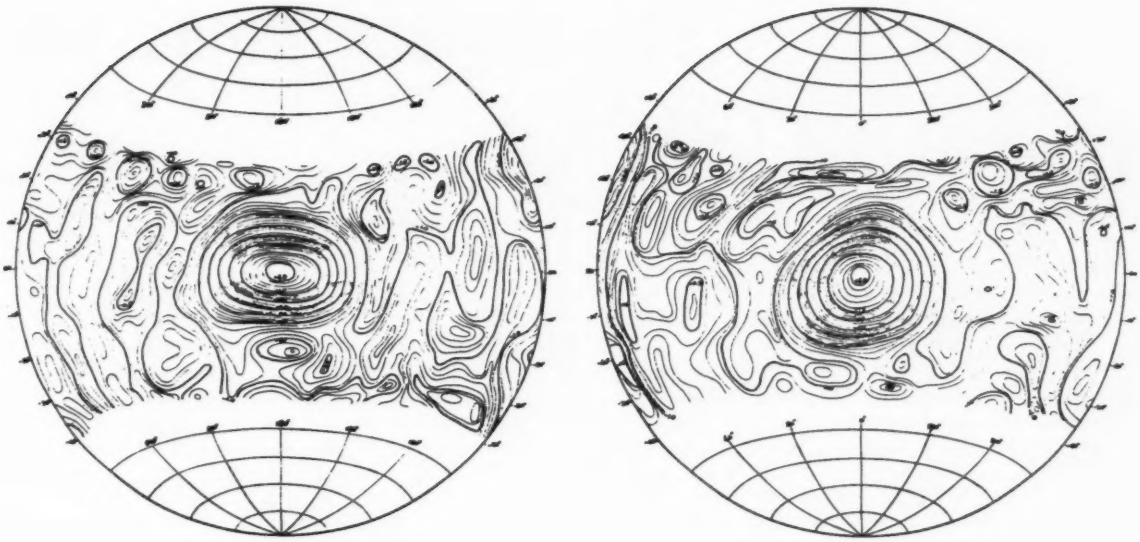

Figure 3. Isophote map of PAGEOS surface midlatitude region from 9 and 27 August 1969 light curves.

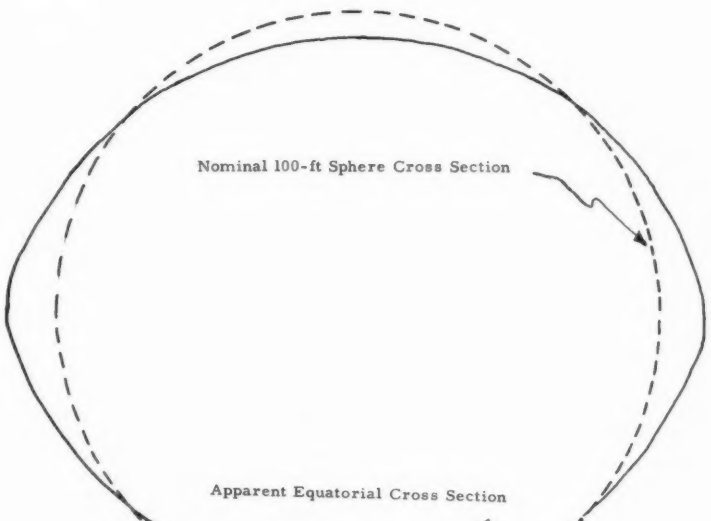

Figure 4. Geometric construction of the PAGEOS equatorial cross section from radii of curvature inferred from photoelectric photometry.

orbit path about the earth. NASA orbit analysts are now attempting a quantitative test of their theory using the ARL data of figure 5.

Although our shape interpretations of the experimental data are not conclusive, they do provide the only measurements of the PAGEOS shape. When the isophote map has been converted in the near future into a topographic one, we anticipate the description of variations of only a few centimeters in the surface. To give the reader a sense of perspective, this will be equivalent to the detection of 1-mm dents and irregularities in a Volkswagen hub cap at a distance of 100 km. We will report on this to the followers of the Air Force Research Review in a future issue.

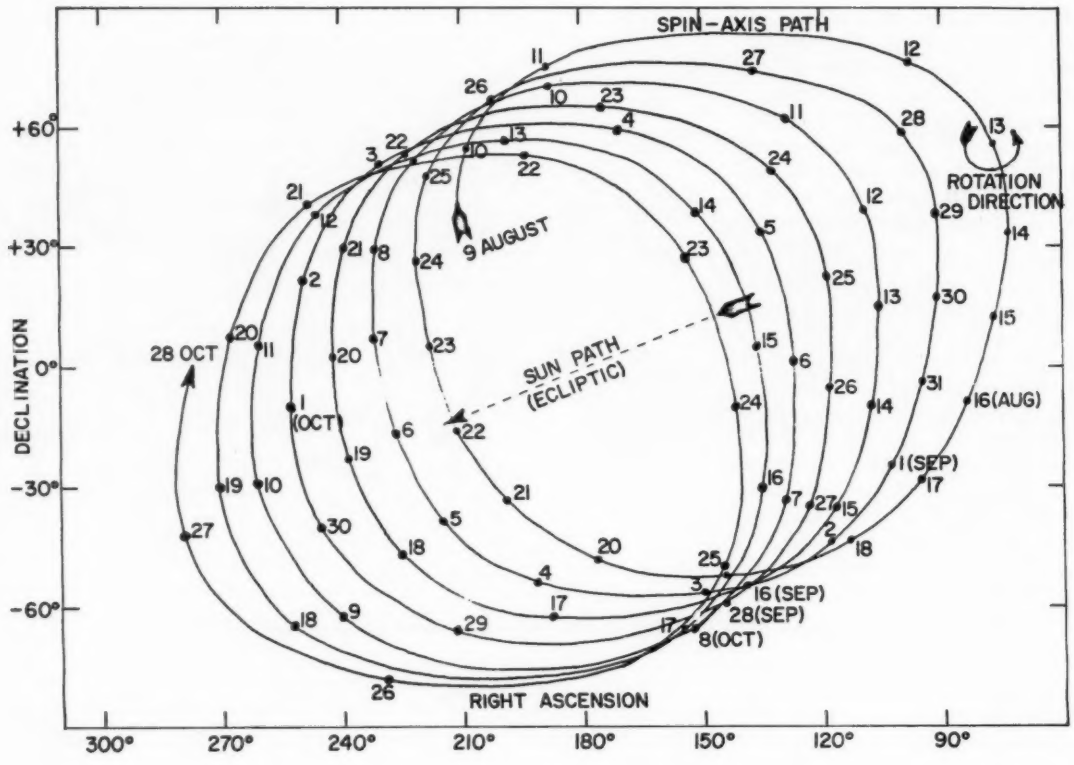

Figure 5. Smoothed spin-axis positions, 9 August - 28 October 1969.

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Mr. Richard C. Vanderburgh, a research space scientist (satellite tracking) with the General Physics Research Laboratory, joined the ARL scientific staff in May 1966. Mr. Vanderburgh's current work includes the collection of optical data with ARL's 24-inch, 4-axis mounted telescope at Sulphur Grove, Ohio, and the refinement of analysis and reduction techniques.

In 1950, Mr. Vanderburgh received his B.A. in Economics from the University of Hawaii. After four years in the Air Force, in December 1955, Mr. Vanderburgh joined Pan American World Airways as a pilot-navigator and, from a San Francisco base, flew scheduled routes throughout the Pacific area and the Orient. He entered the satellite-tracking field as a Smithsonian Baker-Nunn observer at the Hawaii station atop Mt. Haleakala in 1959. From 1961 to 1964, he served as the Smithsonian's Director of Project MOONWATCH, coordinating the efforts of several hundred amateur satellite trackers located throughout the world. He has a number of publications to his credit.

Time Series Analysis And Statistical Meteorology

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It is important from time to time to summarize the life of an Air Force basic research contract for the purpose not only of listing the principal achievements but also of bringing the more important results to the attention of the potential user who might lack time for an extensive literature search. The purpose of this article is to present a brief summary of the more significant Air Force related research results, covering the life of Air Force Contract AF 49(638)-1302 with the Department of Statistics of the Johns Hopkins University. The effort was monitored during the life of the contract, 1 October 1963 to 31 July 1970, by the Directorate of Mathematical and Information Sciences of AFOSR. The contract was directed by Professor R. H. Jones (currently at the University of Hawaii) from October 1963 through June 1968, by Professor D.B. Duncan from July 1968 through October 1969, and by Professor L.J. Gleser from November 1969 through July 1970. This article is based on the final technical report for the contract, prepared by Professor Gleser.

Time series are sequences, discrete or continuous, of quantitative data assigned to specific moments in time and studied with respect to the statistics of their distribution in time (1). They may be simple, consisting of a single numerically given observation at each moment of the discrete or continuous base sequence; or multiple, consisting of a number of separate quantities tabulated according to a time common to all. The runway temperature at 1400 hours at Andrews AFB, tabulated by days, is a simple time series. The runway temperatures at 1400 hours at all Air Force bases in the United States constitute a multiple time series.

The fields of statistical practice in which time series arise divide themselves roughly into two categories: the statistics of economic, sociologic, and short-time biological data, on the one hand; and the statistics of astronomical, meteorological, geophysical, and physical data, on the other. This paper will emphasize results that relate to active areas of Air Force interest.

During the period under review, research was undertaken in several areas of time series analysis, including some work on generalizations of the notion of a time series (e.g., random fields). Emphasis was placed upon developing models, techniques, and statistical criteria that promised to be of practical importance. Special attention was paid to time series problems arising in meteorology, but results obtained have proved useful in such diverse areas as geophysics, process control (e.g., chemical engineering), tracking, and communication. Whenever possible, procedures have been tested on real or simulated data in order to ascertain benefits and limitations.

1. Spectral Analysis and the Periodogram

Although it is well known that the spectrum of a stationary time series can be estimated by using the periodogram, only in the last decade of modern computers and new techniques of computation has this approach become practical. The finite Fourier series transformation of the time series can often be calculated in almost insignificant time. This calculation transforms the data immediately into the frequency domain, whereupon a variety of smoothing techniques are available for estimating the spectrum and functionals of the spectrum, for performing tests of fit for certain models, and for undertaking other tasks of statistical inference. Because of computational difficulties in the 1940s, practitioners had tended to ignore the periodogram. An early paper written under this contract had as its purpose the revival and stimulation of interest in the periodogram approach to time series analysis. Various methods of estimating the spectrum by smoothing the periodogram are compared by a method which avoids defining the bandwidth of a spectral window. This comparison permits a more direct choice among methods.

The advantages of transforming to the frequency domain in cross-spectral analysis are probably greater than the advantages obtained when estimating the spectrum of a univariate series. This fact is pointed out and the method is demonstrated, using daily maximum and minimum temperatures in New York City. The practicality of the periodogram approach has been tested not only on a variety of weather data, but also on other kinds of data.

The demonstrated advantages of the method have prompted several papers investigating the usefulness of the periodogram approach in estimating the innovation variance of a time series (3), in testing various hypotheses about the structure of a univariate time series (4), in testing goodness of fit of autoregressive models for time series (5) and in estimating the parameters in mixed moving-average autoregressive systems (6), in tests of serial independence (7, 8), and in the joint estimation of regression coefficients and the error spectrum for regression problems with stationary errors (9). The last paper also suggests a solution of a problem of special interest in meteorological time series in which spectral estimation must be done in the presence of a nonstationary (i.e. nonconstant) mean. Aspects of this problem are also considered in reference (2).

A dissertation for his Ph.D. by H. T. Davis, under the direction of R. H. Jones, investigated some probabilistic large-sample properties of the periodogram and of functionals of the periodogram. Chapter 5 of the dissertation discusses an estimator of the coherence of a stationary bivariate time series. The moments and a variance-stabilizing transformation are obtained, and tests based on this estimator are suggested for testing the hypothesis that the true coherence equals a given function. Davis's research results also appear in reference (10).

Current research on the periodogram is directed toward improvements to the probabilistic results of Davis and other authors that will enhance construction of smoothed periodogram estimators of the spectrum satisfying certain strong consistency (i.e., large-sample convergence) properties. Some related work done under this contract by M. Pagano is discussed in section 4.

2. Meteorological Time Series

Time series encountered in meteorology frequently exhibit nonstationary behavior. A variable observed at the same time each day appears to be stationary over a period of a few weeks, but has a seasonal variation in structure. For example, the mean and spectrum may differ in the summer and in the winter. A mathematical model for such phenomena was developed by Jones and Brelsford (11). In this model, the structure of the observed time series is assumed to vary periodically, thus presenting an interesting example of a nonstationary time series. They discuss both the formation of predictors of the series based on the past, and the estimation of the parameters and variances involved in such prediction.

Another area of interest concerned with meteorological problems is the estimation of the probability that a certain event will occur (such as the event "it will rain"), when observations are given on certain continuous independent variables during the past and present. Under certain assumptions on the distribution of the independent variables, Brelsford and Jones (11) show that the probability P of the given event is a logit curve (a type of sigmoid curve). They compare performances of two types of estimators of the probability P: estimators derived from the logit model by maximum-likelihood, and estimators obtained by nonlinear regression techniques. Comparisions are also made with a linear regression line, showing conditions under which the linear method results in an acceptable predictor. The techniques are applied both to simulated data and to data obtained from the Weather Bureau. Jones (12) later extended these results to the problem of estimating the probabilities of k mutually exclusive events.

Still another subject of importance in meteorology is numerical weather prediction. Jones (13, 14) discusses his opinion of the appropriate role of statistics in such problems; namely, to aid in the handling of random errors and disturbances. From this point of view, the actual prediction is the solution to a problem in dynamics, but random error enters in observing outcomes and in estimating initial conditions for new predictions. When the initial conditions are observed with error, information from past forecasts can increase the accuracy of the numerical predictions. Jones (13) shows how the techniques of control theory provide an optimal method for combining past forecasts with current observations. The method is demonstrated on simulated nonlinear time series in (14).

3. Multivariate Time Series

Most data obtained in scientific studies are multivariate in nature. This statement is applicable to experiments in meteorology, geophysics, econometrics, communication theory, geography, or physics. In these scientific disciplines, data are not only measured in terms of several variables, but observations on these variables are also obtained over time. Thus, development of a theory of multivariate (multiple) time series is a necessity to enable the interpretations of research data.

During the period 1964–1965 and for two months in 1969, Professor E. J. Hannan of the Australian National University was a full-time visiting research associate at the Johns Hopkins University. Besides writing several papers for the contract, he has also written a comprehensive book (15) on data analysis and inference in multivariate time series. Publication of this book will be a significant milestone in the development of the theory of time series. Approximately 40 percent of the effort in producing this book was provided by the contract.

Exponential smoothing for univariate time series has been widely studied because this technique has many advantages in industrial application. Jones (16) extends this approach to multivariate time series, presenting a recursive method for estimating the optimum weight matrix for exponential smoothing and prediction. A variation of this method allows the estimation to forget the remote past in order to follow a nonstationary process with slowly varying structure over time. Generalizations to nonlinear processes, when the nonlinear structure is known, are indicated, and

the methods are tested on simulated data. Sobel (17) uses a different approach to form predictors for a certain type of nonstationary multivariate process. Other research on prediction and estimation in nonstationary multivariate time series appears in Jones (18).

Adaptive Kalman Updating. Some of the most useful techniques recently developed for the statistical analysis of nonstationary multivariate time series are those of Kalman. His estimators are recursive, being updated over time. D. B. Duncan and P. D. Wilson have recently (19, 20) been working on adaptive methods for smoothing and prediction in nonstationary multivariate time series using Kalman-type models and techniques; their research extends the results of (16).

An important new aspect of their work is the feature of adaptivity in the methods developed for estimation. Kalman's techniques in general require knowledge of the variance-covariance matrices R and Q of the observation and state noise processes, respectively. In the new methods, residual squares and cross-products from the primary state estimation are themselves used as observations, appropriately corrected for bias, in secondary Kalman filters to estimate the parameters R and Q. These estimates are used adaptively in the primary state estimation problem in place of the unknown R and Q matrices.

On the practical side, the research of Duncan and Wilson should prove particularly valuable for problems of tracking and communication. Their methods also have applications in other areas of scientific research (e.g. monitoring hospital patients). Generally, this work will help to disseminate the ideas and results of Kalman estimation theory into areas of multivariate time series analysis where such methods can be of great benefit.

4. Random Fields

Meteorological data are collected in space and time, but this fact is not used in most analyses of meteorological data. If the space-time structure of meteorological data is to be better modeled by random processes, some understanding of processes indexed by points in a topological space (random fields) is needed.

Hannan (21, 22, 23) studied probabilistic properties both of random fields and of other more general stochastic structures. Implications of his research (and the research of other authors) in geophysics are covered in (24), which discuss the Fourier methods that underlie statistical analysis of (1) stationary time series, (2) homogeneous planar processes, (3) homogeneous processes on a sphere, and (4) combinations of stationary time series with either homogeneous planar processes or homogeneous processes on a sphere. The effects on the data of filtering are indicated by a description of the response function of the filter, and the "aliasing" effect is clarified of discrete sampling of continuous phenomena. Procedures for estimating the spectrum of the discrete record are described. Problems of signal measurement in noise (and to some extent their analogs in the measurement of spacial or space-time phenomena) are given as the principal example of the final use of these spectral methods.

Closely related research has recently been completed by M. Pagano in his Ph.D. dissertation, "Some Aspects of a Two-Dimensional Periodogram." Various authors have recommended using the two-dimensional periodogram to estimate the spectral density of a homogeneous planar process. For a real homogeneous process, indexed by a regular lattice in the plane, Pagano delves into various large-sample properties of the periodogram. He shows that under certain regularity conditions on the spectral density, if the random process can be represented as a moving average (in two dimensions) of independent variables obeying the Lindeberg-Feller condition, then the values of the periodogram at distinct points are asymptotically independent, with scaled chi-squared distributions. Further, he shows that the two-dimensional periodogram of the observed random field is approximately the scaled periodogram (where the scale is $4\pi^2$ times the true spectral density) of a random field consisting of independent orthonormal variates—in the sense that the two periodograms converge to one another in the mean. Using an extension to two dimensions of the notion of a Lipschitz class of functions, Pagano finds bounds for the rate of this convergence in the mean. Finally, for a Gaussian random field indexed either by a planar or a toroidal grid, Pagano shows how to construct a consistent sequence of estimators for the spectral density, these estimators being smoothed versions of the two-dimensional periodogram. Approximations to the moderate-sample distribution of such estimators are indicated. Parts of the dissertation are now being revised for publication.

Cohen and Jones (25) have applied some of the known theory of planar processes (and some results in Cohen's dissertation) to certain regression problems in meteorology and geophysics. In these problems, the regressors (independent variables) are observations of a random field. Previous techniques, ignoring the special structure inherent in the problem, had applied classical stepwise regression techniques to select a subset of the regressors for actual prediction. Cohen and Jones show how to obtain a numerical approximation to a Karhunen-Loeve (principal component) expansion of a random field observed at a large number of points, and how to use this expansion to select an appropriate set of regressors. The method is applied to meteorological data.

Further probabilistic study of random fields has been done in a Ph.D. dissertation by Ayala Cohen. More theoretical results appear in (26) in which conditions are given for the existence of the Karhunen-Loeve representation for random fields. The properties of such a representation and its usefulness, when analyzing in homogeneous random fields, are indicated.

5. Other Research

As in most sciences, a constant feedback exists between specialities of statistics. Results obtained in one statistical specialty often have ramifications (or suggest problems) in other specialties. Further, an area of statistical inference, such as time series analysis, can always benefit from deep investigations into the proper goals of data collection and data analysis. Hence, research into other areas of statistics was encouraged during the contract period.

An obvious connection exists between multivariate statistical analysis and multivariate time series analysis, a relationship exploited by many statisticians working in time series. During 1965-1966, partial support was given to research by L. J. Gleser in multivariate linear models. The results of Gleser and Olkin (27) permit tests of hypotheses and estimation of parameters in problems where individuals are randomly assigned to cells in a statistical design and their performances with respect to several attributes are measured over time (multivariate analysis of growth curves).

The end of a classical statistical analysis of data is often a test of no difference between certain parameters (e.g. the analysis of variance). Scientists are slowly realizing that pairwise ranking of such parameters is a more reasonable end product of statistical analysis, particularly since such multiple comparisons are used to verify or reject scientific hypotheses. Two papers by Waller and Duncan (28, 29), which derive from a Ph.D. dissertation by Waller, describe a certain Bayesian decision-theoretic approach to multiple comparisons. The Bayesian aspects of their research have also provided some interesting insights into problems arising in the analysis of nonstationary multivariate time series. Research in multiple comparisons is continuing.

In many scientific problems, the goal of statistical inference is to provide fixed-precision estimators for the structural parameters of a relevant stochastic model, a goal that often requires very large samples. Sequential sampling procedures offer the best hope of keeping sample sizes to a minimum. During 1965–1966, L. J. Gleser began such research (30) and, on his return to the contract in 1969, expanded these research efforts. The eventual aim of this research is to obtain procedures applicable to problems in time series, where the nature of the sampling process (observations are taken over time) lends itself to a sequential approach. Preliminary efforts have been directed to verifying the efficacy of such methods for problems of regression and problems in classical multivariate analysis. Some of the preliminary work has been done by Callahan (31, 32), who worked with Gleser during the summer of 1969. More recent results by Gleser are being consolidated in a technical report which will appear shortly.

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Readers Interchange

It is hoped that the Readers Interchange, under the columns headed "Research Needs" and "Speculative Ideas," will encourage reader participation in suggesting further basic research for the scientist that will lead to new product development for the engineer. As a further source of reader participation, the answers to question 2 of the tear-out page, "Comments to the Editor," of this issue may be published in the Readers Interchange of a subsequent issue (with the permission of the reader).

On the other hand, the column headed "Research Advances," which contains materials furnished by our own research laboratories, and the items in the column headed "Invention Disclosures," which are selected from current invention disclosures originally submitted for possible patent applications, but now released from such action,* may suggest further research for our readers.

Reports of actions stimulated by the Readers Interchange or suggestions for its improvement are welcome.

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**For a more detailed discussion, see "Project: Use It" by Lt Col Ludwig Lippert, Staff Judge Advocate, in the* OAR Research Review, *Vol. IX, No. 3, May-June 1970.*

Speculative Ideas

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Method for Shock Wave Modification

F. Maurer and W. Brungs found experimentally that, by ejecting hydrogen from a spike or from the body nose and by burning it near the boundary between the subsonic and supersonic nose flow region, the drag of the body can be reduced considerably (to 50%) and the shock wave structure can be influenced. Close to the body, the bow wave disappears, while, at a greater distance, the shock wave is increased rather than decreased.

For flight in the transonic region, they suggest an application of this fact. Through heat addition, the stagnation pressure is reduced (the ratio of stagnation pressures q_1 and q_2 is inversely proportional to that of the inflow temperatures T_1 and T_2, $q_1/q_2 = T_2/T_1$). The body can fly at supersonic speeds with respect to the surrounding atmosphere while the stagnation point moves in a heated atmosphere "tube," thus leading to an earlier divergence of the flow lines. The result is an effective increase of body "slenderness" and a decrease of the transonic bow wave.

They conjecture about the technical realization of such inflow heating, as follows: "Beamed heat radiation would not give proper efficiency and transmitted energies. High energy radiations, especially by laser – in nitrogen or oxygen – would be theoretically plausible; however, the duration of the laser pulses and the repetition rate are too small. Hence, such a method, at least for the near future, must be considered as not realizable."

The problem of heated inflow and the idea of laser usage seem to be important for reconsideration and, perhaps, for an extended investigation.

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Test Criteria To Predict the Degradation of Manned Weapons Systems During Combat

Missile tracking systems in combat situations have shown degraded performance when compared to their performance under field test conditions. In the design and testing of such systems, what are the controlling system parameters and human factors, and what consideration must be given to them?

Velocity-controlled tracking, for instance, is apparently degraded less than acceleration-controlled tracking. However, velocity control can be learned easily, while attaining a similar performance in acceleration control requires on the average at least four times as long.

Some studies seem to confirm the hypothesis that the difficulty in learning to handle a system to a certain defined degree is an indicator of the amount of degradation to be expected in combat (increase in CEP). Therefore, learning studies (by nondestructive testing) on a new system would permit an estimate of the efficiency of the manned system in combat, and might also help in the selection of operators. Although such studies have been initiated, more suggestions are required.

New Shape of a Reentry Body

The usual non-lifting reentry body has a blunt, convex, conical nose shape. The pressure distribution on such a shield produces strong lateral forces during reentry into the atmosphere. The occurrence of these forces (size, location, and direction) is somewhat random, resulting in either an unpredictable trajectory deviation or impractical control requirements.

The designer faces a dilemma: either he chooses a blunt disk-type configuration and obtains reasonable attitude stability at the expense of trajectory instability; or he chooses a slender body with good intrinsic trajectory stability, but poor or nonexistent attitude stability.

As a remedy, it is suggested that the shape of the front of the vehicle during reentry be improved to meet the following requirement: no matter what pressure distribution exists on the front, the moments that change the attitude and cause deflection of the trajectory must be kept to a minimum. Therefore,

(1) The body or the body part submerged in the fluid should approach the fluid-dynamically "infinitely slender" shape. (Previously, this requirement was established for water exit and entry, but it can only be partly realized.)

(2) The main resultant force on the body should be directed through the center of gravity, or at least be parallel to the body axis which is in the flight direction. A spherical shape, or a flat plate perpendicular to flight direction, would produce a resultant of the pressure distribution that is essentially through the center of gravity. For example, a circular cone whose vertex is truncated by a cut perpendicular to its main axis should be satisfactory. For proper functioning, it is further essential that:

(a) The front plate should not be corroded.

(b) The edge of the plate should be sharp and not marred, so as to separate the flow evenly.

(c) No large fluctuation of pressure should develop behind the plate. This requirement would effect stabilization of the flow boundary behind the plate by pressurization of the wake space adjacent to the plate.

The problem of keeping the shape and smoothness of the plate, in spite of the pressure and heat load which would develop, merits closer investigation. (For instance, as a hypothetical approach, if the plate is made of titanium carbide and is cooled by lithium which is evaporated into the volume between flow boundary and cone, then behind the plate there would be fluid which vaporizes into the wake. This fluid vapor, which does not react exothermally, should "cool" the body boundary to more extended downstream regions than can be expected with transpiration cooling. With transpiration cooling, the liquid layer over the body surface can probably not be stabilized, as has been suggested in designs of blunted slender cones with coolant flow from the tip (1). Rather the shock boundary layer interaction, at least as shown for a wedge (2), may generate an oscillatory distribution of pressure along the surface, thereby creating hot spots. For exothermal flow behind a plate, periodic recirculatory flows have been demonstrated (DFVLR). This "wake pumping" arrangement would be in effect only during periods of maximum deceleration.)

The following investigations are suggested:

(1) Pressure distribution for blunted slender cones in hypersonic flows.

(2) Pressure distribution for plate blunted slender cones in hypersonic flows.

(3) The wake configuration behind the plate at various rates and types of wake-expanding fluids.

(4) Materials for plate designs.

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Invention Disclosures

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DDC for documentation
on the Air Force contract.

A Method of Measuring the Pressure Dependence of the Thermal Conductivity of Gases

A simple and sensitive method for measuring the pressure dependence of the thermal conductivity of gases has been developed. The method uses the high thermoelectric power of a semiconductor for the accurate measurement of a temperature difference. Data at 25° centigrade for argon, nitrogen, and helium to 300 atmospheres, and carbon dioxide to 1300 atmospheres are given. [Developed by P. J. Fraud, Battelle Memorial Institute, and G. M. Rothberg, Stevens Institute of Technology, under Air Force Contract AF49(638)-1018, AFOSR/SRPS.]

ID-70-11

Electro-Pneumatic Servo Flowmeter

The device consists of a small ceramic bead, 1 mm in diameter, which is a miniaturized, but conventional, ceramic thin film resistance flowmeter, as used for conventional measurement of skin friction and velocity in the aircraft industry. The purpose of the device is to measure velocity profiles of blood flow within the major vessels of man and animals. [Developed by Dr. Grant de J. Lee, Cardiac Department, Radcliffe Infirmary, Oxford, England, under Air Force Contract 61(052)-746, EOAR/SMPPB.]

ID-70-12

Electrogasdynamic Generator Method and Apparatus

A device has been developed which employs a channel through which a fluid moves charged particles against an electric field to generate electric power. High charge density, and thereby efficiency, are maintained by injection of supplemental fluid to prevent the electrostatic repulsion of like charges from entrapping the charged particles in the boundary layer. [Developed by J. J. Rosceiszewski, Convair Division of General Dynamics Corp., Air Force Contract AF49(638)-1556.]

ID-70-13

New Propyl OOF Isomers

This disclosure describes the reaction of dioxygen difluoride (O_2F_2) with perfluoropropylene (C_3F_6) to produce two new OOF compounds: $CF_3CF_2CF_2OOF$ and $CF_3CF(OOF)CF_3$. The OOF radical appears to be transferred to carbon to produce these new compounds which have been structurally characterized by F^{19} NMR and infrared spectroscopy and molecular-weight determination. [Developed by I. J. Solomon, J. N. Keith, and A. J. Kacmarek, IIT Research Institute, Air Force Contract AF49(638)-1175.]

ID-70-14

Transient Data Recorder

A rotating recording head assembly records transient signals on a stationary section of magnetic recording tape. In response to a *tape advance* command, a length of recording tape is rapidly advanced to the recording head assembly from a supply bin and from the assembly to a storage bin. (Developed by T. Palmieri, E. M. Zacharias, Jr., and H. G. Diebler, NUS Corp., Air Force Contract F44620-67-C-0034.]

ID-70-15

Submillimeter Frequency Measuring System

This disclosure describes a simple system for the measurement of frequencies in the submillimeter region of the microwave spectrum utilizing a single MA408B X-Band Video Detector Diode as harmonic generator, mixer, and detector. The same principles employed in this system have been employed at lower frequencies and can probably also be applied at higher frequencies with minor modifications. [Developed by D. Mergerian, Westinghouse Electric Corp., Air Force Contract AF49(638)-1537.]

ID-70-16

Self-Activating Recording Gage

This invention relates to a device in which an electrical signal, generated by a suitable transducer, is used to automatically activate the operating mode of the device and at the same time cause a temporary storage of the electrical signal. The temporary storage provides adequate time for the ensuing operation to compare the stored value with a calibrated reference value and make a permanent record which can be arbitrarily observed and which is directly related to the signal characteristics. [Developed by J. R. Keller, John A. Blume & Associates, Air Force Contract AF49(638)-1739.]

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GPO 910-149

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